We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Bioremediation of Petroleum-Contaminated Soil

Shuisen Chen and Ming Zhong

Abstract

Petroleum is not only an important energy resource to boost the economic development, but also a major pollutant of the soil. The toxicity of petroleum can cause a negative impact on ecosystem, as well as the negative effects related to its carcinogenic for both animals and humans. In the present study, bioremediation as an alternative tool for restoration petroleum-contaminated soils was set forth, and focusing on the phytoremediator plants, petroleum-biodegradable microorganism are responsible for the biodegradation of petroleum. In the present chapter, the bioremediation of petroleum-contaminated soil, as well as the influence factors of bioremediation are elaborated based on the recently studies. This will provide a novel understanding on bioremediation and help improve strategies for petroleum-contaminated soils remediation.

Keywords: petroleum, contaminated soil, bioremediation, phytoremediation, rhizoremediation, biostimulation, bioaugmentation

1. Introduction

Petroleum is an important strategic resource that dominates the world economy [1]. Petroleum is composed of a complex mixture of aromatic hydrocarbons, aliphatic hydrocarbons, heterocyclic hydrocarbons, asphaltenes and non-hydrocarbon compounds. And 60–90% of them are classified as biodegradable [2]. In the past decades, with the development of petroleum industry, petroleum has caused a severe environment contamination and relevant adverse effects during the exploration, transportation, management or storage of hydrocarbons in underground deposits, and refining processes, among which the soil contamination with petroleum is a serious global problem [3].

The petroleum contamination induces oxidative stress, causes the alteration in soil's chemical composition and low nutrient availability. The primary harmful effects of petroleum include inhibition of seed germination, reduction of photosynthetic pigments, slowdown of nutrient assimilation, inhibition of root growth, foliar deformation and tissue necrosis, as well as destroy biological membranes, disturb the signaling of metabolic pathways and disrupt plant roots architecture [4–7]. The low-molecular-weight hydrocarbons can penetrate plant cells resulting in plant death. In addition, the petroleum and its derivatives lead to the development of cancer and other diseases. Previous studies indicated that petroleum contamination caused the depression of the nervous system, narcosis and irritation of the mucous membranes of the eyes in humans [8–11]. In view of the high toxicity, carcinogenic, mutagenic and teratogenic potential of petroleum contamination,

the bioaccumulation of petroleum in the food chain would disturb biochemical and physiological processes which lead directly or indirectly to human health [12, 13]. Therefore, petroleum contamination is not only a negative impetus for plant growth and development but also an adverse factor for human and ecological health.

2. Technologies for petroleum-contaminated soil remediation

Faced with the serious environmental problems that involve the soil contamination by petroleum, an increasing attention has paid to the development and implementation of innovative technologies for the removal of petroleum from soil in the past decades. Multiple soil remediation technologies involve the physical remediation, chemical remediation and bioremediation were developed and employed for the restoration of petroleum-contaminated soil, particularly the eco-friendly bioremediation (Figure 1).

2.1 Physical remediation

Physical remediation uses the physical properties of the contaminants or the contaminated medium to destroy, separate, or contain the contamination, which include soil vapor extraction, flotation, ultrasonication, electro kinetics remediation, thermal desorption and biochar adsorption.

Soil vapor extraction is focus on inducing volatilization of nonaqueous-phase liquid and vapor-phase transport of volatile organic compounds form the subsurface to the surface for subsequent treatment. Soil vapor extraction is also known as in situ soil venting, in situ volatilization, enhanced volatilization, or soil vacuum extraction, in which the extraction well was used to create a pressure or concentration gradient to remove volatiles and some semivolatile contaminants from soil [14]. Soil vapor extraction can remove large quantities of volatile contaminants in uniform soils within a short time. Meanwhile, soil vapor extraction provides oxygen through the flow of air to stimulate the growth of microorganisms. However, the efficiency of soil vapor extraction is affected by soil properties and operational conditions, as well as contaminant properties [15, 16].

The flotation technology relies on the difference in surface properties of both contaminant and soil, which separate oil from soil via a gas–liquid–solid system. The flotation mechanism is dependent on (I) collision between contaminants and

Figure 1. Schematic of the remediation strategies for petroleum-contaminated soil remediation.

bubbles, (II) form bubble-contaminant with the attachment of contaminants and bubble, (III) flotation of bubble-contaminant based on difference in buoyancy and detachment of contaminant from bubble-contaminant [17]. Flotation is characterized as simplicity, low operational cost and high efficiency for contaminants removal. It also can separate very small or light weight particles with low settling velocities. Nevertheless, large amounts of wastewater were produced during the flotation process. And the efficiency of aged or weathered contaminated soil was significantly decreased [18].

The ultrasonication helps desorption of the contaminant and promotes the formation of strong oxidant, hydroxyl radicals ($\text{OH}\cdot$) which enhance the efficiency of pollutant removal [16, 19]. Ultrasonication can eliminate the hazardous pollutants without any chemicals. Moreover, the on-spot heating and intense agitation will enhances heat and mass transfer processes. However, the higher energy consumption for generation of acoustic makes it the costly setup [20].

Electro kinetics remediation employs direct electric current between appropriately distributed electrodes (cathodes and anodes) that embedded in petroleum-contaminated soil to form an electric field. The voltage potential gradient were formed in the electric field which cause the fluid medium to flow preferentially towards the cathode and drag the contaminant together with the bulk flow [21]. The advantage of electro kinetics remediation is speed of execution and low operating cost. Moreover, the electro-osmotic flow is constant through the entire soil mass during the remediation which more suitable for low permeability soils. However, the electro kinetic process is ineffective in low contaminant concentration. The alteration of soil pH and hot spots around the electrodes were induced after an extended period of time [16].

Thermal desorption based on the manipulation of temperatures to increase the vapor pressure of the contaminants, in which the contaminants were volatilized and subsequent desorption from contaminated soil [22]. Thermal desorption is very effective in destroying the oil pollutants under high heat condition. In addition, thermal desorption emits little or no contamination gas into the atmosphere. However, only the volatile contaminants were removed by thermal desorption [23].

Biochar is carbon-enriched and porous with high specific surface area and biodegradability. The biochar was employed as an amendment to implement organic contaminated soil remediation due to the surface adsorption, partition and sequestration [24, 25].

2.2 Chemical remediation

Chemical oxidation has the potential for rapidly deposing or preprocessing soil contaminants. Oxidants that can cause the rapid and complete chemical destruction of petroleum contaminants are employed in the chemical oxidation remediation. In chemical oxidation, the contaminants is oxidation chemically converts to non-hazardous, at least, biodegradable products or less toxic compound that more stable, less mobile or inert [16, 26].

Plasmas oxidation is also considered as highly competitive technology to remediating the pollutants from soils. Especially the plasma technology based on pulsed corona discharge and dielectric barrier discharge has aroused widely concerns in soil remediation [27, 28]. Plasma are macroscopically electrically neutral aggregates composed of numerous ions, electrons, atoms, molecules and unionized neutral particles. A number of active constituents such as O_3 , H_2O_2 , the hydroxyl radicals ($\text{OH}\cdot$) and high energy electrons were generated in the generation of plasma by ionization, in which a strong oxidizing environment was created for oxidative decomposition of contaminants [29].

Photocatalytic degradation is effective for decomposition of polycyclic aromatic hydrocarbon in the soils. This technology makes use of the semiconductor metal oxide as catalyst to degrading organic pollutant into small molecules directly [30]. Semiconductor molecule contains a valance band with stable energy electrons and an empty higher energy conduction band. The absorption of radiation can initiate the photocatalytic reaction, in which the formation of holes (h^+) in valence band and electrons (e^-) in conduction band in femtosecond time scale. During the photocatalytic process, the hydroxyl radicals ($OH\cdot$) and superoxide radical anion ($O_2^{\cdot-}$) are formed to degrading organic pollutant. However, the light absorption characteristics, humic substances content and moisture content of soil may affect the photocatalytic degradation [31, 32].

2.3 Bioremediation

The physical and chemical remediation have their own characteristics, even effective for higher contaminants removal. However, the practical applications are impracticable under some circumstances, such as the remediation of amount of contaminated soil is economically impracticable. Furthermore, most of the physical and chemical remediation technologies are unavoidable to destroy the soil microbiota that reduces the concentration of soil at the expense of damaging the integrity of soil ecosystem [33]. Therefore, alternative technologies that have less environmentally aggressive, greater ease of practical application, as well as more efficient and cost-effective for environmental decontamination are expected. In the past decades, significant advances on bioremediation have been achieved. Although it is time consuming, bioremediation techniques, due to their eco-friendly approach and very low cost, efficient and sustainable for restoring the contaminated soil in the context of sustainability, are extensively noticeable at present [34].

Bioremediation is a process that naturally or artificially take advantage of living organisms or their products to reduce (degrade, detoxify, mineralize or transform) the pollutants of the contaminated environment [35]. For this purpose, living organisms (plants and microorganisms) that tolerate and have capacity to grown under contaminated soil are usually used. Number of studies has revealed that selecting petroleum-tolerant plants for bioremediation in cases of soil petroleum pollution is a feasible and sustainable technology. Many plants, such as perennial ryegrass, alfalfa, *Mirabilis jalapa*, were considered as tolerant to petroleum stress [36–38]. The microorganisms that are utilized in petroleum pollutants removal can be bacteria, fungi or yeasts. These microbes are the essential component in soil ecological systems that play a vital role for the remediation of petroleum hydrocarbon and other pollutants [39, 40]. Some of them have high capacity to degrade contaminants and widely used for environmental depollution [41]. In the bioremediation of petroleum contaminated soils, the most widely used organisms are bacteria which have high frequency, rapid growth and a broad spectrum of degradation of petroleum products [42].

Phytoremediation is a kind of bioremediation. Phytoremediation is considered as an alternative technology that makes use of plants and microorganisms associated with their root to degrade or reduce soil contaminants [43]. The main factors to consider when choosing a plant as a phytoremediator are root system, plant survival and its adaptability to prevailing environmental conditions. Plants not only can degrade petroleum pollutants directly via enzymatic activities, but also can stimulate the rhizosphere microbial community to degrade petroleum contaminants [44]. The use of plant growth promoting rhizobacteria (PGRR) plays an important role in phytoremediation. The PGRR promote the growth of plant by providing phytohormones and mineral nutrition. PGRR can also generate antibiotics, compete for

nutrients with pathogens or induce systemic resistance in the host plant to protect it from pathogens [45]. To understand the interactions between PGRR and plants would be better reveal the alleviation of contaminants toxicity of soil.

Rhizoremediation is a strategy for phytoremediation, plant act indirectly in phytoremediation, since their presence in the environment provides favorable conditions for the growth of microorganisms in the rhizosphere region. The rhizosphere is a soil zone ranging from the surface to a depth of 1–5 mm, in which the interdependence between plants and microorganisms result in a symbiotic lead to form a symbiotic relationship [46]. Plants roots can release the organic acids, carbohydrates, amino acid and oxygen to the rhizosphere, which promote the development of rhizosphere microbe (including bacteria, fungi, protists, nematodes and in vertebrates). And the microbe benefits the plant by providing the necessary vitamins, cytokinins and amino acids to promote plant growth [16]. The development of microbial biotechnology is beneficial for screening and identifying microorganisms from petroleum contaminated soils [47]. Many microorganisms have been isolated and utilized as biodegraders for petroleum hydrocarbons disposal. More than 79 genera of bacteria that capable of degrading petroleum hydrocarbons have been identified [48]. Furthermore, some microorganisms were crucial for petroleum hydrocarbons since the abundance of these microorganisms were dominant increased after petroleum contamination [49]. In view of different indigenous bacteria have different catalytic enzymes, the combination of multiple functional bacteria were preferable to remediating the pollutants in contaminated soils. Previous studies showed that the joint action of indigenous bacterial consortium and exogenous bacteria were effectively accelerating the degradation of petroleum [50].

Biostimulation is one of the main strategy bioremediation for the decontamination of petroleum-polluted soil, which through adjusting the environmental conditions (temperature, moisture, pH, redox potential, aeration, mineral nutrition) to enhance the growth and the metabolic activity of indigenous degrading microbial populations. The microorganisms' activity in biostimulation practice is tolerant to various hydrocarbons and can utilized hydrocarbons as carbon sources for their growth [51].

Bioaugmentation is another strategy of bioremediation, which refer to the inoculation of exogenous microorganisms into the contaminated soils to degrade the target contaminants [52]. The inoculated microorganism can be one strain or a consortium of microbial strains with diverse functional degradation capacities [53]. Bioaugmentation was considered to be more effective for the degradation of the light fraction (C₁₂-C₂₃) of petroleum hydrocarbons [54]. Bioaugmentation can divided into cell bioaugmentation and genetic bioaugmentation based on the degradation mechanism of the inoculated strains. Cell bioaugmentation relies on the survival and catabolic activity of the inoculated strains to accelerate the degradation of target contaminants directly [55]. While genetic bioaugmentation based on the spread of catabolic genes (plasmids, integrons or transposons mediated) into native microbial populations. And then the native acquiring these genes achieve the ability to degrade organic contaminants [56]. As compare to the cell bioaugmentation, genetic bioaugmentation, especially plasmid-mediated bioaugmentation appears to have greater potential for the bioremediation of contaminated soils [57].

In addition, microbial electrochemical system was considered as an emerging technique for bioremediation, which integrates microbial and electrochemical processes to convert the pollutants to less-toxic or value-added products [58]. With various inherent advantages, microbial electrochemical system was mostly applied in remediation of petroleum contaminants in soil. Microbial electrochemical system

is considered as more flexible for various contaminants in bioremediation due to the oxidation and reduction transformation in remediation processes [59].

3. Influence factors of bioremediation

Bioremediation is viewed as a technique to accelerate the natural biodegradation process in a cost-effective and environment friendly way. However, bioremediation is time consuming, and the contaminant concentration and composition, temperature, soil pH, oxygen condition and salinity are highly affected the bioremediation of the petroleum-contaminated soils.

The plants and microbes would unable to grow in a high petroleum soil. In that case, the bioremediation was inoperative or low efficiency. In addition, some of the petroleum derivatives with high solubility have higher cytotoxicity to biodegradation bacterial, while other compounds produced no significant inhibitory effects on bacterial growth [60].

The temperature plays a vital role in bioremediation and influence biodegradation reactions [61]. Indeed, temperature can indirectly affecting biodegradation efficiency by affecting bacterial growth and metabolism, altering soil matrix and the mode of occurrence of pollutants [62].

Petroleum and its derivatives can full fill the interstices of soil, which reduce the amount of oxygen in soils. Under reduced or absent oxygen conditions, the metabolism of aerobic microorganisms was partially interrupted, as well as the bioavailability and degradation efficiency of pollutant were reduced [12, 63].

The key components of biodegradation of petroleum hydrocarbons are various specific enzymes [61]. The alterations of pH value may influence the enzymes activities to reduce the effective of the biodegradation. In other hand, alterations of pH and high salinity may inhibit microbial growth and metabolism. In addition, the lack of technique to monitor the survival and activity of the organism in soil also limited the application of bioremediation.

4. Conclusions

Bioremediation is an eco-friendly and economic method to remove the petroleum pollutants of soil. There were several kinds of bioremediation have been applied to remediate the petroleum hydrocarbon from contaminated soils, such as phytoremediation, rhizoremediation, biostimulation, bioaugmentation, and so on. The petroleum-tolerant plants and the high-effective petroleum degradation microbes are preferable used in bioremediation process. Alternatively, construction of the different functional bacterial consortium or genetic engineering bacteria, and potentially using integrated bioremediation approaches for bioremediation of petroleum have become a trend in future. However, some of the influence factors are significant reduced the degradation efficiency on bioremediation application. Therefore, use a combination of bioremediation and other technologies is effective strategy to accelerate for petroleum hydrocarbon pollutants removal. Furthermore, developing and enriching the novel technologies of bioremediation remains far off.

Acknowledgements

This research was supported by Scientific Research Foundation for the Introduction of Talent of Shenyang Agricultural University (Program No. 88481607).

Conflict of interest

The author declares no conflict of interest.

IntechOpen

IntechOpen

Author details

Shuisen Chen* and Ming Zhong
Key Laboratory of Agricultural Biotechnology of Liaoning Province, College of
Bioscience and Biotechnology, Shenyang Agricultural University, Shenyang, China

*Address all correspondence to: shuisenchen@syau.edu.cn

IntechOpen

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Sun Y. On-site management of International Petroleum Cooperation Projects. Natural Gas Exploration and Development. 2009;**32**(2):69-73. DOI: 10.3969/j.issn.1673-3177.2009.02.019
- [2] Falkova M, Vakh C, Shishov A, Zubakina E, Moskvina A, Moskvina L, et al. Automated IR determination of petroleum products in water based on sequential injection analysis. Talanta. 2016;**148**:661-665. DOI: 10.1016/j.talanta.2015.05.043
- [3] Smith E, Thavamani P, Ramadass K, Naidu R, Srivastava P, Megharaj M. Remediation trials for hydrocarbon-contaminated soils in arid environments: Evaluation of bioslurry and biopiling techniques. International Biodeterioration & Biodegradation. 2015;**101**:56-65. DOI: 10.1016/j.ibiod.2015.03.029
- [4] Redondo-Gómez S, Petenello MC, Feldman SR. Growth, nutrient status, and photosynthetic response to diesel-contaminated soil of a cordgrass, *Spartina argentinensis*. Marine Pollution Bulletin. 2014;**79**:34-38. DOI: 10.1016/j.marpolbul.2014.01.009
- [5] Rahbar FG, Kiarostami K, Shirdam R. Effects of petroleum hydrocarbons on growth, photosynthetic pigments and carbohydrate levels of sunflower. Journal of Food, Agriculture and Environment. 2012;**10**:773-776
- [6] Nardeli SM, Saad CF, Rossetto P de B, Caetano VS, Ribeiro-Alves M, Paes JES, et al. Transcriptional responses of *Arabidopsis thaliana* to oil contamination. Environmental and Experimental Botany. 2016;**127**:63-72. DOI: 10.1016/j.envexpbot.2016.03.007
- [7] Zhang J, Fan S, Yang J, Du X, Li F, Hou H. Petroleum contamination of soil and water, and their effects on vegetables by statistically analyzing entire data set. Science of the Total Environment. 2014;**476-477**:258-265. DOI: 10.1016/j.scitotenv.2014.01.023
- [8] Bezza FA, Nkhalambayausi Chirwa EM. Biosurfactant from *Paenibacillus dendritiformis* and its application in assisting polycyclic aromatic hydrocarbon (PAH) and motor oil sludge removal from contaminated soil and sand media. Process Safety and Environmental Protection. 2015;**98**:354-364. DOI: 10.1016/j.psep.2015.09.004
- [9] Ameen F, Moslem M, Hadi S, Al-Sabri AE. Biodegradation of diesel fuel hydrocarbons by mangrove fungi from Red Sea Coast of Saudi Arabia. Saudi Journal of Biological Sciences. 2016;**23**:211-218. DOI: 10.1016/j.sjbs.2015.04.005
- [10] Bastida F, Jehmlich N, Lima K, Morris BEL, Richnow HH, Hernández T, et al. The ecological and physiological responses of the microbial community from a semiarid soil to hydrocarbon contamination and its bioremediation using compost amendment. Journal of Proteomics. 2016;**135**:162-169. DOI: 10.1016/j.jprot.2015.07.023
- [11] Al Shami A, Harik G, Alameddine I, Bruschi D, Garcia DA, El-Fadel M. Risk assessment of oil spills along the Mediterranean coast: A sensitivity analysis of the choice of hazard quantification. Science of the Total Environment. 2017;**574**:234-245. DOI: 10.1016/j.scitotenv.2016.09.064
- [12] Chen M, Xu P, Zeng G, Yang C, Huang D, Zhang J. Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: Applications, microbes and future research needs. Biotechnology Advances.

2015;**33**:745-755. DOI: 10.1016/j.biotechadv.2015.05.003

[13] Rein A, Adam IKU, Miltner A, Brumme K, Kästner M, Trapp S. Impact of bacterial activity on turnover of insoluble hydrophobic substrates (phenanthrene and pyrene)-model simulations for prediction of bioremediation success. *Journal of Hazardous Materials*. 2016;**306**:105-114. DOI: 10.1016/j.jhazmat.2015.12.005

[14] Baker RS, Bierschenk J. Vacuum-enhanced recovery of water and NAPL: Concept and field test. *Soil and Sediment Contamination*. 1995;**4**:57-76

[15] Albergaria JT, Alvim-Ferraz M d CM, Delerue-Matos C. Remediation of sandy soils contaminated with hydrocarbons and halogenated hydrocarbons by soil vapour extraction. *Journal of Environmental Management*. 2012;**104**:195-201. DOI: 10.1016/j.jenvman.2012.03.033

[16] Lim MW, Lau EV, Poh PE. A comprehensive guide of remediation technologies for oil contaminated soil—Present works and future directions. *Marine Pollution Bulletin*. 2016;**109**:14-45. DOI: 10.1016/j.marpolbul.2016.04.023

[17] Tao D. Role of bubble size in flotation of coarse and fine particles—A review. *Separation Science and Technology*. 2005;**39**:741-760. DOI: 10.1081/SS-120028444

[18] Wang J, Yin J, Ge L, Zheng J. Using flotation to separate oil spill contaminated beach sands. *Journal of Environmental Engineering*. 2010;**136**:147-151. DOI: 10.1061/(ASCE)EE.1943-7870.0000117

[19] Zhang J, Li J, Thiring RW, Hu X, Song X. Oil recovery from refinery oily sludge via ultrasound and freeze/thaw. *Journal of Hazardous Materials*. 2012;**203-204**:195-203. DOI: 10.1016/j.jhazmat.2011.12.016

[20] Son Y, Nam S, Ashokkumar M, Khim J. Comparison of energy consumptions between ultrasonic, mechanical, and combined soil washing processes. *Ultrasonics Sonochemistry*. 2012;**19**:395-398. DOI: 10.1016/j.ultsonch.2011.11.002

[21] Ranjan RS, Qian Y, Krishnapillai M. Effects of electrokinetics and cationic surfactant cetyltrimethylammonium bromide [CTAB] on the hydrocarbon removal and retention from contaminated soils. *Environmental Technology*. 2006;**27**:767-776. DOI: 10.1080/09593332708618686

[22] Rushton DG, Ghaly AE, Martinell K. Assessment of Canadian regulations and remediation methods for diesel oil contaminated soils. *American Journal of Applied Sciences*. 2007;**4**:465-578. DOI: 10.3844/ajassp.2007.465.478

[23] Falciglia PP, Giustra MG, Vagliasindi FGA. Low-temperature thermal desorption of diesel polluted soil: Influence of temperature and soil texture on contaminant removal kinetics. *Journal of Hazardous Materials*. 2011;**185**:392-400. DOI: 10.1016/j.jhazmat.2010.09.046

[24] Tang J, Zhu W, Kookana R, Katayama A. Characteristics of biochar and its application in remediation of contaminated soil. *Journal of Bioscience and Bioengineering*. 2013;**116**:653-659. DOI: 10.1016/j.jbiosc.2013.05.035

[25] Wu S, He H, Inthapanya X, Yang C, Lu L, Zeng G, et al. Role of biochar on composting of organic wastes and remediation of contaminated soils—A review. *Environmental Science and Pollution Research International*. 2017;**24**:16560-16577. DOI: 10.1007/s11356-017-9168-1

[26] Jalilian Ahmadkalaei SP, Gan S, Ng HK, Abdul Talib S. Evaluation of ethyl lactate as solvent in Fenton

- oxidation for the remediation of total petroleum hydrocarbon (TPH)-contaminated soil. Environmental Science and Pollution Research International. 2017;**24**:17779-17789. DOI: 10.1007/s11356-017-9382-x
- [27] Wang TC, Qu G, Li J, Liang D. Evaluation of the potential of soil remediation by direct multi-channel pulsed corona discharge in soil. Journal of Hazardous Materials. 2014;**264**:169-175. DOI: 10.1016/j.jhazmat.2013.11.011
- [28] Ognier S, Rojo J, Liu Y, Duten X, Cavadias S, Thannberger L. Mechanisms of pyrene degradation during soil treatment in a dielectric barrier discharge reactor. Plasma Processes and Polymers. 2014;**11**:734-744. DOI: 10.1002/ppap.201300077
- [29] Li R, Liu Y, Mu R, Cheng W, Ognier S. Evaluation of pulsed corona discharge plasma for the treatment of petroleum-contaminated soil. Environmental Science and Pollution Research International. 2017;**24**:1450-1458. DOI: 10.1007/s11356-016-7929-x
- [30] Dong D, Li P, Li X, Zhao Q, Zhang Y, Jia C, et al. Investigation on the photocatalytic degradation of pyrene on soil surfaces using nanometer anatase TiO₂ under UV irradiation. Journal of Hazardous Materials. 2010;**174**:859-863. DOI: 10.1016/j.jhazmat.2009.09.132
- [31] Hoffmann MR, Martin ST, Wonyong C, Bahnemann DW. Environmental applications of semiconductor photocatalysis. Chemical Reviews. 1995;**95**:69-96. DOI: 10.1021/cr00033a004
- [32] Cheng M, Zeng G, Huang D, Lai C, Xu P, Zhang C, et al. Hydroxyl radicals based advanced oxidation processes (AOPs) for remediation of soils contaminated with organic compounds: A review. Chemical Engineering Journal. 2016;**284**:582-598. DOI: 10.1016/j.cej.2015.09.001
- [33] Gómez-Sagasti MT, Epelde L, Alkorta I, Garbisu C. Reflections on soil contamination research from a biologists point of view. Applied Soil Ecology. 2016;**105**:207-210. DOI: 10.1016/j.apsoil.2016.04.004
- [34] Azubuike CC, Chikere CB, Okpokwasili GC. Bioremediation techniques-classification based on site of application: Principles, advantages, limitations and prospects. World Journal of Microbiology and Biotechnology. 2016;**32**:180. DOI: 10.1007/s11274-016-2137-x
- [35] Gouda S, Kerry RG, Das G, Paramithiotis S, Shin H-S, Patra JK. Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. Microbiological Research. 2018;**206**:131-140. DOI: 10.1016/j.micres.2017.08.016
- [36] Günther T, Dornberger U, Fritsche W. Effects of ryegrass on biodegradation of hydrocarbons in soil. Chemosphere. 1996;**33**:203-215
- [37] Peng S, Zhou Q, Cai Z, Zhang Z. Phytoremediation of petroleum contaminated soils by *Mirabilis jalapa* L. in a greenhouse plot experiment. Journal of Hazardous Materials. 2009;**168**:1490-1496. DOI: 10.1016/j.jhazmat.2009.03.036
- [38] Shahsavari E, Adetutu EM, Anderson PA, Ball AS. Tolerance of selected plant species to petrogenic hydrocarbons and effect of plant rhizosphere on the microbial removal of hydrocarbons in contaminated soil. Water, Air, and Soil Pollution. 2013;**224**:1495. DOI: 10.1007/s11270-013-1495-3
- [39] Yan L, Sinkko H, Penttinen P, Lindström K. Characterization of successional changes in bacterial community composition during bioremediation of used motor oil-contaminated soil in a boreal climate.

Science of the Total Environment. 2016;**542**:817-825. DOI: 10.1016/j.scitotenv.2015.10.144

[40] Jia J, Zong S, Hu L, Shi S, Zhai X, Wang B, et al. The dynamic change of microbial communities in crude oil-contaminated soils from oil fields in China. *Soil and Sediment Contamination: An International Journal*. 2017;**26**:171-183. DOI: 10.1080/15320383.2017.1264923

[41] Kuppusamy S, Thavamani P, Venkateswarlu K, Lee YB, Naidu R, Megharaj M. Remediation approaches for polycyclic aromatic hydrocarbons (PAHs) contaminated soils: Technological constraints, emerging trends and future directions. *Chemosphere*. 2017;**168**:944-968. DOI: 10.1016/j.chemosphere.2016.10.115

[42] Wolicka D, Suszek A, Borkowski A, Bielecka A. Application of aerobic microorganisms in bioremediation in situ of soil contaminated by petroleum products. *Bioresource Technology*. 2009;**100**:3221-3227. DOI: 10.1016/j.biortech.2009.02.020

[43] Brzeszcz J, Steliga T, Kapusta P, Turkiewicz A, Kaszycki P. R-strategist versus K-strategist for the application in bioremediation of hydrocarbon-contaminated soils. *International Biodeterioration & Biodegradation*. 2016;**106**:41-52. DOI: 10.1016/j.ibiod.2015.10.001

[44] Hall J, Soole K, Bentham R. Hydrocarbon phytoremediation in the family Fabaceae—A review. *International Journal of Phytoremediation*. 2011;**13**:317-332. DOI: 10.1080/15226514.2010.495143

[45] Jéssica Janzen dos S, Maranhão LT. Rhizospheric microorganisms as a solution for the recovery of soils contaminated by petroleum: A review. *Journal of Environmental Management*. 2018;**210**:104-113. DOI: 10.1016/j.jenvman.2018.01.015

[46] Newman MM, Lorenz N, Hoilett N, Lee NR, Dick RP, Liles MR, et al. Changes in rhizosphere bacterial gene expression following glyphosate treatment. *Science of the Total Environment*. 2016;**553**:32-41. DOI: 10.1016/j.scitotenv.2016.02.078

[47] Guerra AB, Oliveira JS, Silva-Portela RCB, Araújo W, Carlos AC, Vasconcelos ATR, et al. Metagenome enrichment approach used for selection of oil-degrading bacteria consortia for drill cutting residue bioremediation. *Environmental Pollution*. 2018;**235**:869-880. DOI: 10.1016/j.envpol.2018.01.014

[48] Tremblay J, Yergeau E, Fortin N, Cobanli S, Elias M, King TL, et al. Chemical dispersants enhance the activity of oil- and gas condensate-degrading marine bacteria. *The ISME Journal*. 2017;**11**:2793-2808. DOI: 10.1038/ismej.2017.129

[49] Yakimov MM, Timmis KN, Golyshin PN. Obligate oil-degrading marine bacteria. *Current Opinion in Biotechnology*. 2007;**18**:257-266. DOI: 10.1016/j.copbio.2007.04.006

[50] Tao K, Liu X, Chen X, Hu X, Cao L, Yuan X. Biodegradation of crude oil by a defined co-culture of indigenous bacterial consortium and exogenous *Bacillus subtilis*. *Bioresource Technology*. 2017;**224**:327-332. DOI: 10.1016/j.biortech.2016.10.073

[51] Shahi A, Aydin S, Ince B, Ince O. Evaluation of microbial population and functional genes during the bioremediation of petroleum-contaminated soil as an effective monitoring approach. *Ecotoxicology and Environmental Safety*. 2016;**125**:153-160. DOI: 10.1016/j.ecoenv.2015.11.029

[52] Ruffini Castiglione M, Giorgetti L, Becarelli S, Siracusa G, Lorenzi R, Di Gregorio S. Polycyclic aromatic

- hydrocarbon-contaminated soils: Bioaugmentation of autochthonous bacteria and toxicological assessment of the bioremediation process by means of *Vicia faba* L. Environmental Science and Pollution Research International. 2016;**23**:7930-7941. DOI: 10.1007/s11356-016-6049-y
- [53] Heinaru E, Merimaa M, Viggor S, Lehist M, Leito I, Truu J, et al. Biodegradation efficiency of functionally important populations selected for bioaugmentation in phenol- and oil-polluted area. FEMS Microbiology Ecology. 2005;**51**:363-373. DOI: 10.1016/j.femsec.2004.09.009
- [54] Bento FM, Camargo FAO, Okeke BC, Frankenberger WT. Comparative bioremediation of soils contaminated with diesel oil by natural attenuation, biostimulation and bioaugmentation. Bioresource Technology. 2005;**96**:1049-1055. DOI: 10.1016/j.biortech.2004.09.008
- [55] Singh A, Ward OP. Biotechnology and Bioremediation—An overview. In: Singh A, Ward OP, editors. Biodegradation and Bioremediation. Berlin, Heidelberg: Springer; 2004. pp. 1-17. DOI: 10.1007/978-3-662-06066-7_1
- [56] Wiedenbeck J, Cohan FM. Origins of bacterial diversity through horizontal genetic transfer and adaptation to new ecological niches. FEMS Microbiology Reviews. 2011;**35**:957-976. DOI: 10.1111/j.1574-6976.2011.00292.x
- [57] Garbisu C, Garaiyurrebaso O, Epelde L, Grohmann E, Alkorta I. Plasmid-mediated bioaugmentation for the bioremediation of contaminated soils. Frontiers in Microbiology. 2017;**8**. DOI: 10.3389/fmicb.2017.01966
- [58] Wang X, Cai Z, Zhou Q, Zhang Z, Chen C. Bioelectrochemical stimulation of petroleum hydrocarbon degradation in saline soil using U-tube microbial fuel cells. Biotechnology and Bioengineering. 2012;**109**:426-433. DOI: 10.1002/bit.23351
- [59] Wu Y, Jing X, Gao C, Huang Q, Cai P. Recent advances in microbial electrochemical system for soil bioremediation. Chemosphere. 2018;**211**:156-163. DOI: 10.1016/j.chemosphere.2018.07.089
- [60] Hou N, Zhang N, Jia T, Sun Y, Dai Y, Wang Q, et al. Biodegradation of phenanthrene by biodegradation-producing strain *Achromobacter* sp. LH-1 and the study on its metabolisms and fermentation kinetics. Ecotoxicology and Environmental Safety. 2018;**163**:205-214. DOI: 10.1016/j.ecoenv.2018.07.064
- [61] Varjani SJ, Upasani VN. A new look on factors affecting microbial degradation of petroleum hydrocarbon pollutants. International Biodeterioration & Biodegradation. 2017;**120**:71-83. DOI: 10.1016/j.ibiod.2017.02.006
- [62] Abed RMM, Al-Kharusi S, Al-Hinai M. Effect of biostimulation, temperature and salinity on respiration activities and bacterial community composition in an oil polluted desert soil. International Biodeterioration & Biodegradation. 2015;**98**:43-52. DOI: 10.1016/j.ibiod.2014.11.018
- [63] Martínez Álvarez LM, Lo Balbo A, Mac Cormack WP, Ruberto LAM. Bioremediation of a petroleum hydrocarbon-contaminated Antarctic soil: Optimization of a biostimulation strategy using response-surface methodology (RSM). Cold Regions Science and Technology. 2015;**119**:61-67. DOI: 10.1016/j.coldregions.2015.07.005